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Characteristic Variations of Sea Surface Temperature with Multiple Time Scales in the North Pacific

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ABSTRACT

Temporal evolution and spectral structure of sea surface temperature (SST) anomalies in the North Pacific over the last 37 years are investigated on the three characteristic time scales: shorter than 24 months (HF), 24–60 months (ES), and longer than 60 months (DC). The leading empirical-orthogonal function (EOF) for the DC time scale is characterized by a zonally elongated monopole centered at around 40°N, 180°. The leading EOF for the HF time scale is somewhat similar to that for the DC time scale, although there are two centers of action with the same polarity at the mid and western Pacific. The leading EOF for the ES time scale, however, exhibits a different pattern whose center of action at the mid Pacific is located farther southeastward.

In the time evolution of the SST anomalies associated with the leading EOF of the DC time scale, several anomaly periods can be identified that last five years or longer. The transition from a persistent period to another with the opposite polarity is generally very brief, except for the one that lasts throughout the late 1960s.

The EOF analysis was repeated separately on these persistent anomaly periods and the long transition period. The spatial structure of the leading EOF of the SST variability with the ES time scale is found to be sensitive to the polarity of the decadal anomaly. These results are suggestive of the possible influence of the decadal SST variability upon the spatial structure of the variability with shorter time scales.

1. Introduction

Recently, an increasing number of studies have been done on interannual variability in the atmospheric and oceanic systems, with a particular emphasis on the decadal time scale, in order to understand climatic change. It is unclear whether the recent warming trend in the global air temperature is really due to the increase of greenhouse gases or merely a manifestation of the natural variability with decadal or longer time scales. Decadal scale variations in sea surface temperature (SST) and the atmospheric circulation over the North Pacific have been reported by Nitta and Yamada (1989) and Trenberth (1990). Nitta and Yamada (1989) showed that the time index of the leading empirical-orthogonal function (EOF) of the global SST exhibits significant variability with the decadal time scale, although it is somewhat masked by fluctuations with shorter time scales superimposed. Their SST difference map between the two decades of 1967–76 and 1977–86 exhibits a north–south oscillating pattern in the North Pacific, with substantial cooling in the midlatitudes. Trenberth (1990) pointed out that the Aleutian Low was extraordinarily intensified in the 1976/77 winter and has been anomalously strong in most of the winters in the late 1970s through mid-1980s. In these studies, the recent deepening of the Aleutian Low is found to be associated with the PNA (Pacific/North American) teleconnection pattern (Wallace and Gutzler 1981), which may have a significant relationship with the persistent positive SST anomalies observed over the eastern equatorial Pacific starting in the mid-1970s.

There are many studies that have focused on phenomenon using the specific time scales, such as the El Niño/Southern Oscillation (ENSO) and Quasi-Biennial Oscillation (QBO) (e.g., Hanawa et al. 1988; Yasunari 1987, 1991; Barnett 1991). Hanawa et al. (1988) investigated the phases of the ENSO cycle in the various SST anomalies in the western North Pacific. In the composite maps, they showed that a well-organized SST anomaly pattern is observed in the winter during an ENSO warm event in the western North Pacific, and the polarity of the anomaly tends to reverse in the following winter.

Watanabe (1989) showed the existence of dominant QBO signals in the SST variability over the western North Pacific, where wintertime SST variability is in-

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fluenced by the strength of the cold surges from the Eurasian Continent. The sign of the SST anomaly tends to remain the same throughout the warm season, and an anomaly with the opposite sign tends to be developed in the following winter. As suggested by Barnett (1991), there may be no meaningful relationship between the stratospheric QBO and the QBO in the SST field. The mechanism of the QBO in SST is still unclear, but ocean dynamics seem to play an important role. Subtropical mode water in the northwestern part of the North Pacific subtropical gyre, formed in strong wintertime convection, may retain its wintertime condition for the next several months, while being advected by the Kuroshio recirculation current (Suga et al. 1989; Suga and Hanawa 1990).

The studies mentioned above suggest that there may be several different characteristic time scales in the SST field, at least in the North Pacific. Barnett (1991) investigated the interactions among variability with annual, quasi-biennial (20–30 months), and longer (36–80 months) time scales in the SST and sea level pressure fields over the tropical Pacific. It may be possible that the ocean–atmosphere interaction in the extratropics occurs in its own active manner rather than as a passive medium against the impact from the tropics. In fact, Wallace and Jiang (1987) demonstrated that the atmospheric response in the Northern Hemisphere to the SST variability in the equatorial Pacific is substantially different from that to the SST variability over the North Pacific. Since the amplitude of the variance is generally larger in the tropics, particularly over in the eastern equatorial Pacific, the variability in the low latitudes may mask the extratropical signals. Therefore, we will limit our analysis to the extratropical Northern Pacific, where many more ship measurements of SST are available than in the tropics. In addition, our results might be useful for interpreting the results of numerical models in which the response of the global atmospheric circulation to the SST change imposed in the tropics and extratropics is simulated (Blackmon et al. 1983; Pitcher et al. 1988; Lau and Nath 1990; Kitoh 1991; Kushnir and Lau 1992). In this study, we will first show the dominant spatial patterns in SST anomalies over the North Pacific and their temporal evolution for each of these time scales. Second, we will focus on decadal variability in the ocean–atmosphere system, which may be regarded as the basic state for the shorter time-scale fluctuations. We will try to clarify the relationship among these time scales.

The remaining part of this paper is organized as follows. In section 2, the data processing in the present study is described. In section 3, an EOF analysis is applied to the SST fluctuations with three characteristic time scales as extracted through filters. In section 4, the atmospheric variability associated with decadal SST fluctuations is examined. In section 5, the relationship between the decadal variability and that with shorter time scales is discussed. Conclusions and discussion will be given in section 6.

2. Dataset

In the present study, we made a new monthly 5° × 5° (latitude × longitude) gridded dataset for SST over the North Pacific for the period from 1950 through 1986 in the same manner as in Iwasaka and Hanawa (1990) and based on the raw dataset (Compressed Marine Reports) in the Comprehensive Ocean Atmosphere Data Set (COADS) rather than the monthly trimmed dataset. The data before 1950 were not used because the measurements were few and not taken by the intake method (Barnett 1984), although Folland et al. (1984) suggests corrections that can be applied to the data prior to 1950.

It was found that the grid boxes within the areas in the midlatitudes contain a sufficient number of qualified measurements throughout the entire 37-year period for obtaining reliable statistics for SST. The data outside of these areas were excluded from the EOF analysis, but they were included in the composite analysis later on.

Monthly mean fields of 500-hPa geopotential height on 10° × 10° (latitude × longitude), provided by the Japan Meteorological Agency, were used to identify large-scale atmospheric patterns associated with the SST variability.

For each of these variables we computed a climatological-mean annual cycle for the entire period at each grid point, and the anomalies were defined as a departure from that cycle.

3. Dominant EOFs in the characteristic time scales

We will extract the SST signals separately with the following three characteristic time scales from the previous studies mentioned in the Introduction:

(i) the HF (high-frequency) time scale (periods shorter than 24 months),

(ii) the ES (El Niño cycle) time scale (periods between 24 and 60 months), and

(iii) the DC (decadal) time scale (period longer than 60 months),

by using a four pole, Butterworth recursive filter, as in Murakami (1979) and Kushnir and Wallace (1989). Figure 1 shows the response functions of the two filters. Although this filter requires only three data points for each time step, it has fairly sharp cutoff and induces no significant phase shift in the filtered time series. The bandpass filtering is performed by subtracting the 60-month lowpass and 24-month highpass-filtered time series at a particular time from a unfiltered time series at the same time.

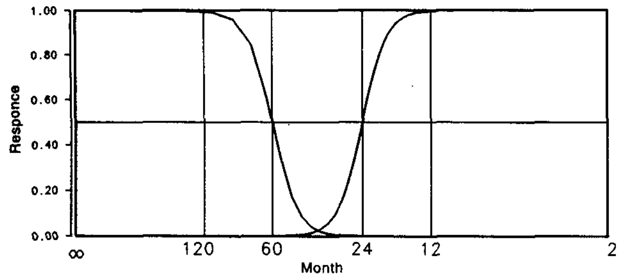


FIG. 1. Response functions of the digital filters used in this study.

The large-scale SST variability in the North Pacific has been investigated through EOF analysis by Weare et al. (1976), Iwasaka et al. (1987), and Nitta and Yamada (1989) and others. The leading EOF obtained in each of these studies is characterized by an elliptical-shaped monopole centered at the middle of the basin. The evolutions of the corresponding time coefficients, however, exhibit some differences, one from another, probably due to the difference in the period for the analysis. Furthermore, fluctuations of time coefficients seemed to have various time scales, therefore, it was difficult to interpret interannual variability due to the presence of high-frequency fluctuations.

We performed an EOF analysis for the unfiltered SST anomaly time series from 1950 through 1986. Figure 2a shows the first EOF, which is very similar to the dominant EOFs obtained in the previous studies (Weare et al. 1976; Iwasaka et al. 1987; Nitta and Yamada 1989). This mode accounts for 18.5% of the total variance. The spectrum of the time coefficient of this mode (Fig. 2b) exhibits several peaks of the frequency bands that correspond to three characteristic time scales. Therefore, one might speculate that the same anomaly pattern dominates over all three time scales. In order to see whether this is the case, we repeated the EOF analysis on the filtered time series for each of the time scales separately.

Figures 3a–c show the first EOFs for the HF, ES, and DC time scales, respectively. The pattern for the DC time scale (Fig. 3c, which explains 36.8% of the total DC variance and 8.5% of the unfiltered total variance), which is characterized by an elliptical monopole centered around 40°N, 180°, accompanied by anomalies with the opposite polarity along the North American coast, strongly resembles the first EOF of the unfiltered SST. The pattern over the eastern half of the Pacific for the HF time scale (11.8% and 6% of the HF and unfiltered variance, respectively; Fig. 3a) resembles that for the DC time scale but with the center of action located eastward at around 40°N, 160°W, and with another center of action with the same polarity at around 25°N, 125°E, in the western half.

The EOF for the ES time scale (29.9% and 4% of the ES and unfiltered variance, respectively; Fig. 3b), however, is somewhat different from those for other time scales: the mid-Pacific center is shifted southeastward considerably, and now the western Pacific is covered by anomalies with the opposite polarity. Most of the significant positive values of the time coefficient in Fig. 3b correspond to the ENSO cold events (La Niña; 1955/56, 1966/67, 1970/71, 1980/81, and 1983/84), and most of the negative values to the ENSO warm event (El Niño; 1957/58, 1965/66, 1968/69, 1972/73, and 1982/83). This result confirms that the North Pacific SST anomalies with this time scale are strongly influenced whether directly or indirectly by tropical atmosphere–ocean interactions, although they might be somewhat modulated by interactions within the extratropics. In fact, the correlation analysis by Wallace and Jiang (1987) reveals that the response in

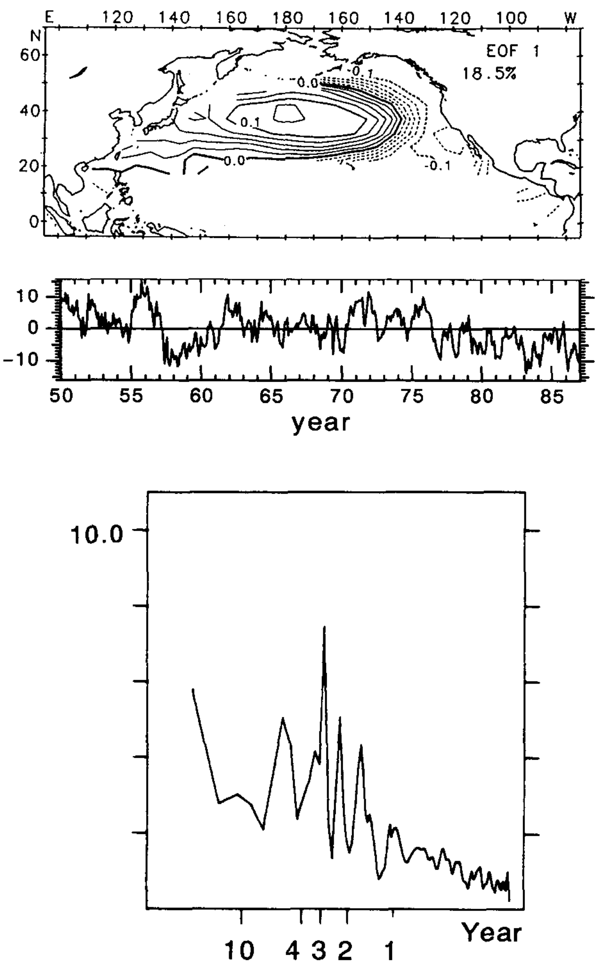
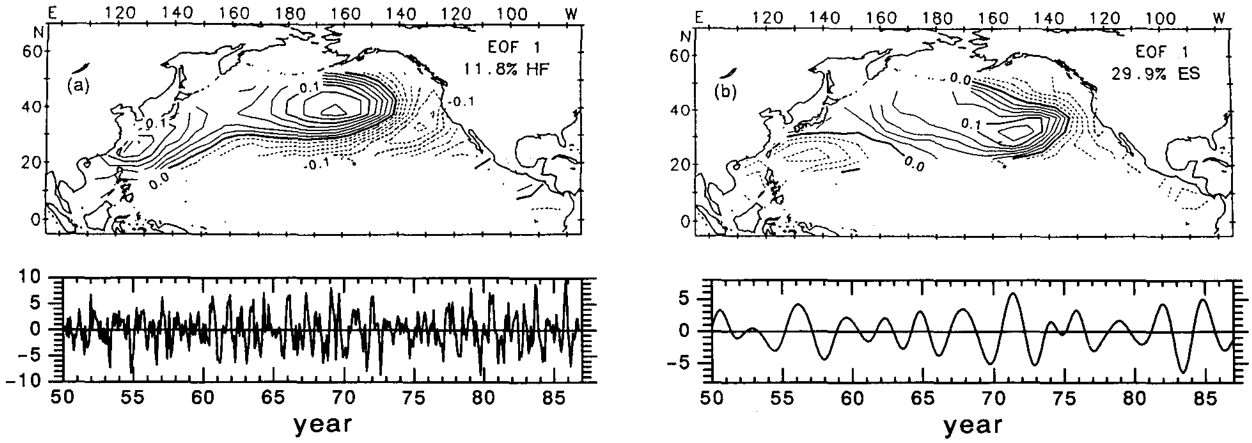


FIG. 2. (a) Distribution map of the first EOF of SST in the North Pacific (upper panel) and its time coefficient (lower panel). This mode can account for 18.5% of the total variance. The contour interval is 0.02. Solid (dashed) lines represent positive (negative) value; (b) spectrum of the time coefficient of the first EOF mode shown in Fig. 2a.



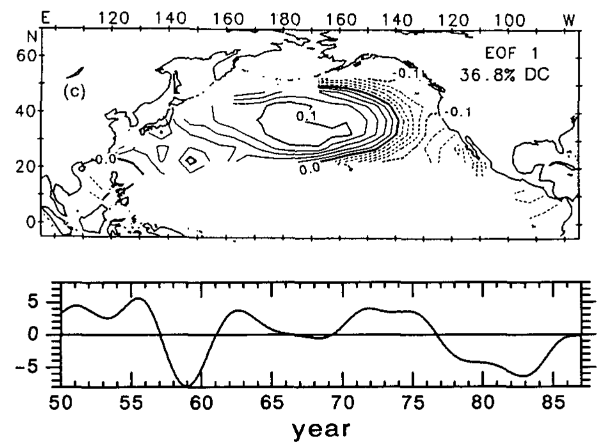


FIG. 3. (a) Same as in Fig. 2a but for the HF time scale. This mode can account for 11.8%; (b) same as in Fig. 2a but for the ES time scale. This mode can account for 29.9%; (c) same as in Fig. 2a but for the DC time scale. This mode can account for 36.8%.

the 500-hPa height to the North Pacific SST anomalies exhibits a structure very similar to the PNA pattern, whereas the atmospheric response to the SST anomalies in the equatorial Pacific is quite different from the PNA pattern that is associated with SST fluctuations in the midlatitudes.

The confidence level of the EOFs were evaluated by using the Monte Carlo approach, that is, the "rule N" proposed by Preisendorfer (1988). The EOF analysis was repeated on each of one-hundred sets of the randomized data. The variance of each of the several leading modes accounts for only less than 3% of the total variance. This result indicates that the leading EOFs of the SST field stand out against the noise level. We also examined the sampling errors in the eigenvalues of these leading EOFs in the manner of North et al. (1982). The first EOFs for the unfiltered anomaly and ES time scales are well separated from the second EOFs for those, whereas trivial degeneracies and mixing of eigenvalues may occur in the HF time scale. However, we could hardly evaluate in the DC time scale due to the small number of degrees of freedom on that time scale.

4. Decadal variability in the ocean and atmosphere

The decadal SST variability in the North Pacific has been investigated by Royer (1989) and Nitta and Yamada (1989). In the present study, we will investigate that variability in more detail by extracting it through the use of digital filters from our quality-checked dataset. As mentioned above, the first EOF in the DC time scale explains a considerable fraction (36.8%) of the total DC variance.

In the temporal evolution of the first EOF for the DC time scale (Fig. 3c), we can recognize a quasi-steady anomaly period immediately followed by another persistent anomaly period with the opposite polarity. Based on the value of time coefficients of that mode (X_i), the individual years were categorized into three periods, as follows: the L+ period (18 year; 1950–56, 1961–64, 1970–76) for $X_i > +2.0$ unit (unit is arbitrary); L− (13 years; 1957–60, 1977–85) for $X_i < -2.0$ unit; and L0 (6 years; 1965–69 and 1986) for $|X_i| < 2.0$.

Figure 4 shows the composite maps of the unfiltered SST anomalies averaged over these three periods. For

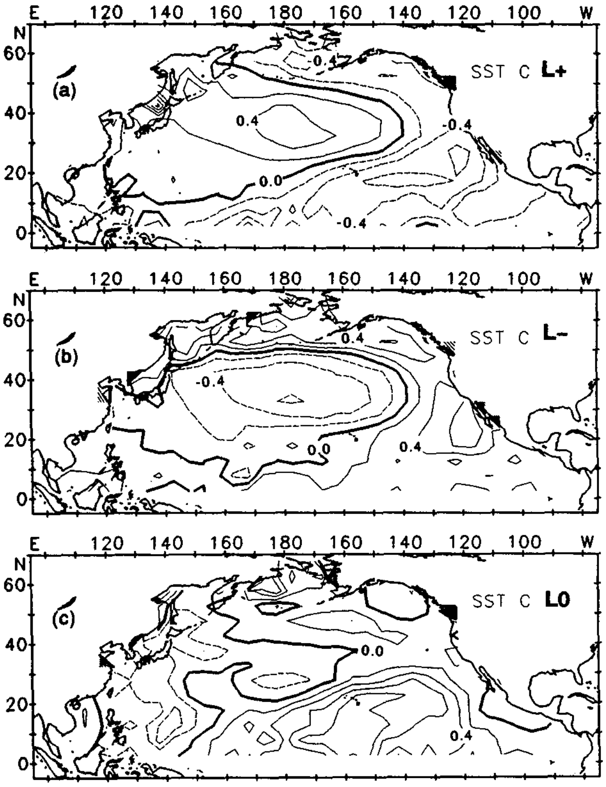


FIG. 4. Composite maps of unfiltered SST anomalies for the periods (a) L+, (b) L−, and (c) L0. The contour interval is 0.2. Positive (negative) values are represented by solid (dashed) lines.

the periods of the L+ and L−, the extratropical SST anomalies are characterized by the pattern associated with the first EOF, while the anomalies with opposite polarity dominate over the tropics at least for the L+ period. The result indicates a decadal fluctuation in the equator to pole gradient of SST over the Pacific Ocean. Our results agree well with those of Nitta and Yamada (1989) and Trenberth (1990). The L0 period pattern is characterized by noisy, almost normal SST anomalies in the extratropics and a large positive anomaly in the southeastern part of the domain. The confidence level was evaluated by using a Student's t-test. The anomalies during the period of the L+ and L− is above the 95% confidence level.

The corresponding composite maps of the three wintertime anomalies of the 500-hPa geopotential height are shown in Fig. 5. For the L− period, the Pacific jet stream tends to be extended farther down stream than normal, associated with PNA-like anomalies. For the L+ period, in contrast, the midlatitude westerlies tend to be weaker.

5. The relationship between the decadal anomalies and variability with shorter time scales

The quasi-steady SST anomalies associated with the decadal variability may be considered the basic state for the SST fluctuations with shorter time scales. Namias et al. (1988) showed that the persistence of the SST anomalies within individual years fluctuates with much longer time scales, indicative of the possible influence of the decadal variability on the activity of the high-frequency fluctuations. Barnett (1991) investigated the relationship between the quasi-biennial oscillation (20–30 months) and the variability with lower frequencies (36–80 months) of tropical SST and SLP fields, using bicoherence as an indicator of the interaction. Since we focus on the influence of the decadal SST anomalies on the structure of the SST variability with higher frequencies, we once again applied the EOF

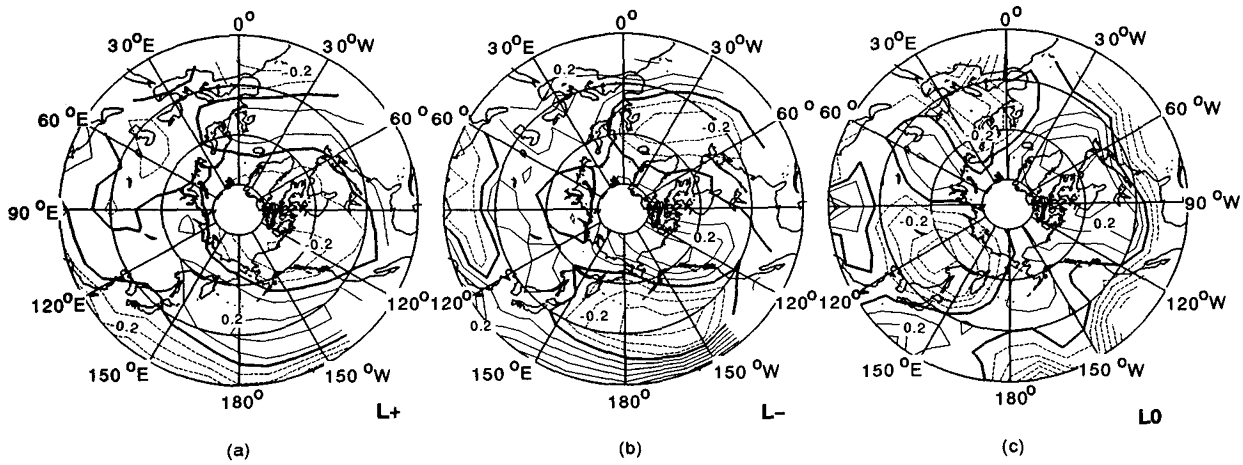


FIG. 5. Same as in Fig. 4, but for wintertime (December through February) anomalies of 500-hPa geopotential height corresponding to states of DC scale for the periods (a) L+, (b) L−, and (c) L0. The anomaly at each grid point is normalized by its standard deviation. Positive (negative) values are represented by solid (dashed) lines.

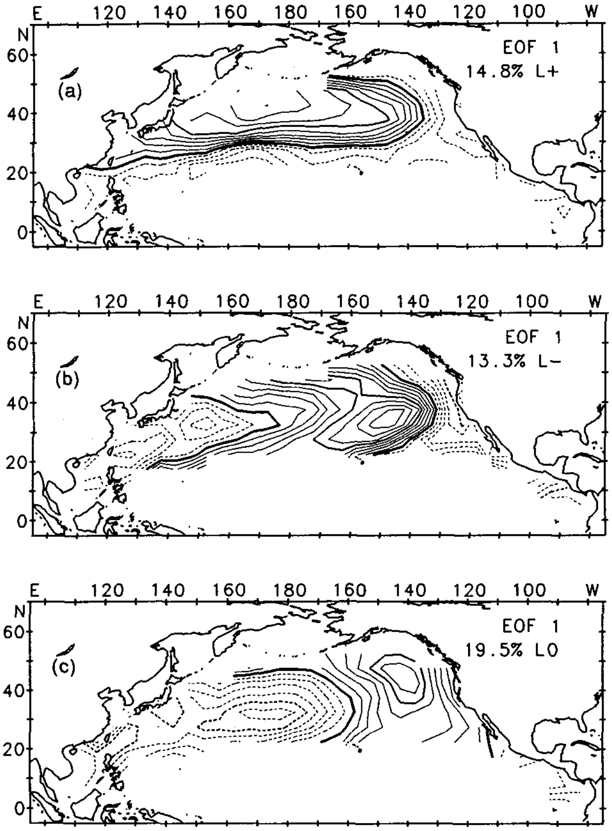


FIG. 6. Same as in Fig. 2a but for SST variability around the long-term average in the periods (a) L+, (b) L−, and (c) L0.

analysis rather than compute the bicoherence. Before this analysis, SST anomalies were recalculated relative to the mean for the three periods (L+, L−, and L0). The first EOFs of the unfiltered SST anomalies for these periods are shown in Fig. 6 (L+ UN, L− UN, L0 UN), and those of the filtered SST anomaly fields for the HF and ES time scales are shown in Figs. 7 and 8 (L+ ES, L− ES, and L0 ES), respectively.

We extract the patterns for L+ UN and L+ ES EOFs in which a zonally elongated pattern appears in the midlatitudes as in the previous section. Therefore, it can be said that this pattern is the most basic pattern of SST variation in the North Pacific. The patterns of the EOFs for the period of L− (L− UN and L− ES) are quite different from those for the period L+, whereas they are very similar to the pattern in the ES time scale as shown in Fig. 3b. The pattern of the EOFs for the period of L0 (L0 UN and L0 ES) is rather different from the above patterns and is more like an east–west oscillation.

These results show a sensitivity of the temporal structure of SST field, that is, the variability in the ES time scale is modulated by states of the DC time scale. In the HF time scale, however, variability is independent of the DC time scale because the EOFs of the three periods for the HF time scale are almost the same. The present results strongly suggest the coupled ocean–atmosphere system does not work independently at a given time scale.

We evaluate the robustness of three patterns mentioned above. We select several months when the time index of each of the first EOF for the three periods have significant values with both polarities. A zonally elongated pattern (cf., Figs. 6a and 8a; L+ UN, L+ ES) is shown in the SST anomaly maps (not shown) in those months during the period of L+. In those months during the period of L−, the patterns of the SST anomaly are very similar to that of the EOF for the period of L− (cf., Figs. 6b and 8b; L− UN, L− ES).

6. Conclusion and discussion

In the present study, we have investigated the temporal evolution and spectral structure of SST variations in the North Pacific on the three characteristic time scales: HF (less than 24 months), ES (24–60 months), and DC (more than 60 months) scales. An EOF analysis reveals that a zonally elongated monopole structure is dominant in the midlatitude anomalies with the DC

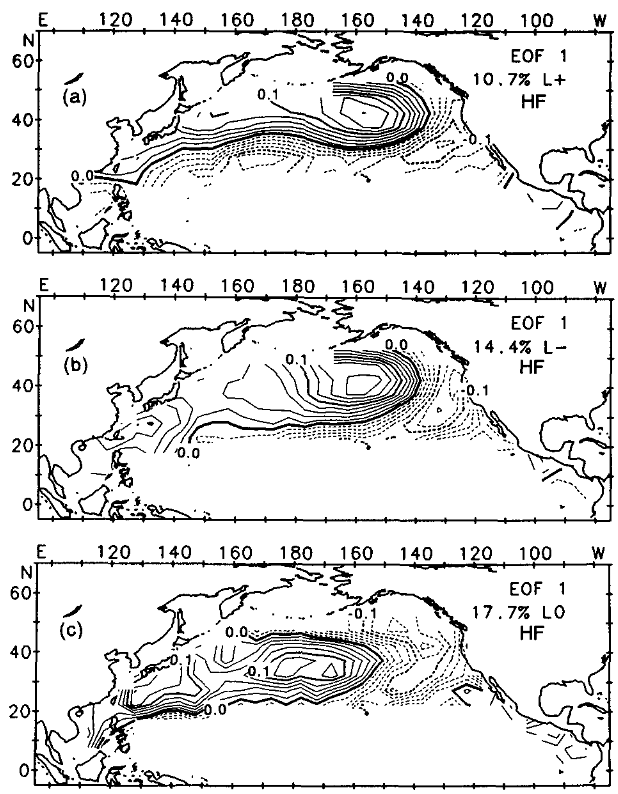


FIG. 7. Same as in Fig. 6 but for the HF time scale.

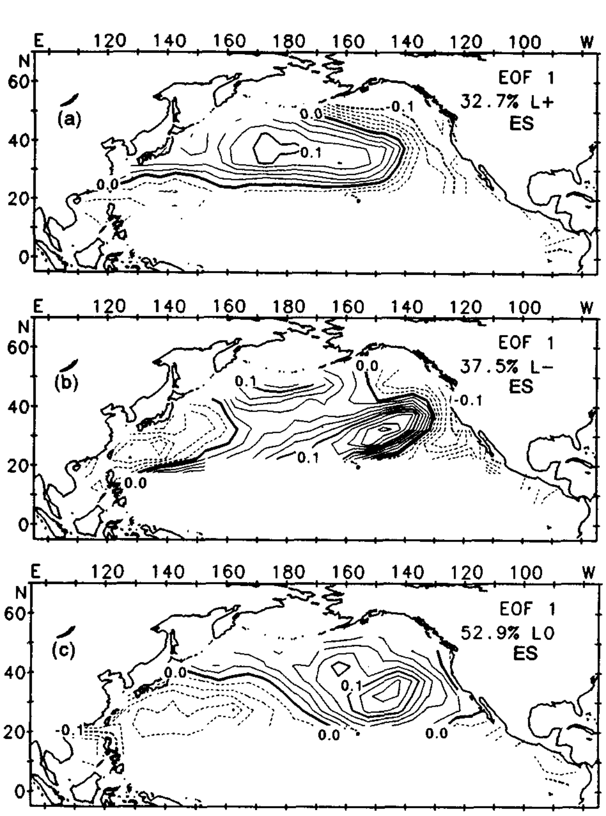


FIG. 8. Same as in Fig. 6 but for the ES time scale.

time scale, which is associated with the PNA-like anomalies in the tropospheric circulation. The time coefficient of the first EOF exhibits several persistent anomaly periods, each of which is followed, in general, by a brief transition period. The structure of the leading EOF of the SST variability with the ES time scale is found to be sensitive to the polarity of the anomaly associated with the decadal variability.

The spatial patterns shown in sections 4 and 5 are not sensitive to the selection of time-scale bands. The sensitivity to band selection was checked by repetitions of EOF analysis for other cutoff periods (e.g., 18 and 72 months) as the HF, ES, and DC time scales. The intermediate band for the ES time scale was also examined through analyses of narrower time-scale bands. Some studies reported variability in the biennial time scales in the ocean and atmosphere in the midlatitudes (Barnett 1991; Watanabe 1989), although such a time scale is combined into the ES time scale. When the intermediate band was divided into two bands, the influence of the decadal variability to the spatial structure was reproduced in both biennial and ES time scales. Furthermore, studies should address whether the biennial time scale is a result of amplitude modulation of ENSO events, or whether there is another meaningful mechanisms at work.

The dataset used in the present study is not long enough to extract statistically significant signals, especially at the decadal time scale. We should take care to interpret the present results, although the robustness of pattern was checked.

Ocean dynamics such as the spin up or down of the gyres may cause the decadal variability in SST field. Levitus (1989) demonstrated that the North Atlantic subtropical gyre was colder and fresher during the early 1970s than during the early 1950s, indicative of the spin down of the gyre in between. A similar change in the subtropical gyre was also detected in the western North Pacific with a decadal time scale by Bingham et al. (1992). Such long-term changes in the oceanic condition may occur due to the feedback process in the interactive ocean–atmosphere system, which may maintain a quasi-steady state for several years.

Interactions may have different mechanisms at different characteristic time scales. It has been reported that the winter SST anomalies in the midlatitudes may effectively work as a boundary condition for the atmospheric general circulation in numerical experiments (Palmer and Sun 1985; Kitoh 1988, 1991; Lau and Nath 1990; Kushnir and Lau 1992). Therefore, we believe that not only the atmospheric effect on the ocean but also the oceanic effect on the atmosphere act to establish some time-scale variations of the ocean–atmosphere system in the midlatitudes. To clarify the mechanisms, further studies will be needed.

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